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(54) DIFFUSION BONDING OF METALLIC PARTS

(71) We, FULMER RESEARCH INSTITUTE LIMITED, a British company, of Hollybush Hill, Stoke Poges, Buckinghamshire, do hereby declare the invention for which we pray that a patent may be granted to us and the method by which it is to be performed to be particularly described in and by the following statement:—

This invention is concerned with the diffusion bonding of metallic parts.

Diffusion bonding is a means of joining metal parts without forming the large volumes of cast metal typical of fusion welding and without causing bulk deformation and recrystallisation as occurs with pressure welding. By diffusion bonding, alloys which are not usually considered to be weldable can be joined without a change in structure at the interface; it is especially important when fusion welding cannot be used. Examples of alloys to which diffusion bonding has been applied include (i) titanium alloys, where the reactivity of the molten alloy will cause a fusion weld to lack toughness due to contamination with oxygen and nitrogen, and (ii) dispersion strengthened nickel alloys in which the structure would be so altered by fusion welding as to reduce high temperature strength.

It is generally recognised that there are three broad techniques for effecting diffusion bonding:

(i) use of an elevated temperature and high pressure for a short time, this technique also being known as "high pressure solid state bonding",

(ii) use of an elevated temperature and low pressure for a relatively long time, this technique also being known as "low pressure solid state bonding", and

(iii) use of a metallic interlayer which gives rise to a transient liquid phase between the parts to be joined.

The present invention is not concerned with the first two techniques, but with a development of the third technique. Specifically, the present invention is based on the discovery that improved diffusion bonds can be obtained between parts formed of certain metals and alloys, including titanium alloys, niobium or niobium alloys and nickel alloys, by using (depending on the metal parts to be bonded) magnesium, tin, aluminium or a combination of aluminium and copper layers as an interlayer between the parts to be bonded.

According to one aspect of the present invention, therefore, we provide a process for bonding two metal parts which are formed of the same or different materials selected from titanium alloys, niobium or niobium alloys, and nicked alloys, which comprises providing an interlayer formed of magnesium or tin between the parts to be bonded, and maintaining the assembly of the parts to be bonded and the interlayer under sufficient pressure to keep the integers of the assembly in contact over the desired bond area and heating at a sufficiently high temperature to cause the formation of a liquid phase due to melting of the interlayer material or of a eutectic mixture formed between the interlayer material and either of the parts to be bonded, the amount of interlayer material present being such that no insoluble intermetallic compound is formed between the interlayer material and either of the parts to be bonded, the pressure and temperature being maintained until the liquid phase has diffused into the metal parts, and the assembly being maintained under a protective atmosphere during heating when one or both of the parts is formed of a titanium alloy or niobium or a niobium alloy.

According to other aspects of the invention, other combinations of metallic parts to be bonded and interlayer materials that may be used are as follows.

A combination of aluminium and copper layers may be used as the interlayer material for bonding a combination of metallic parts as referred to above, that is formed of a titanium alloy, niobium or a niobium alloy,

or a nickel alloy, and also for bonding a first part formed of a titanium alloy or niobium or a niobium alloy to a second part formed of stainless steel. This latter combination of metal parts, i.e. including a stainless steel part, can also be bonded using a magnesium interlayer, although for this combination of metal parts, it is preferred to use an aluminium/copper combination as the interlayer material.

Additionally, aluminium alone can be used as the interlayer material for bonding parts, each formed of a titanium alloy, niobium or a niobium alloy of a nickel alloy.

Where the parts to be bonded are of the same type, for example they are both formed of a titanium alloy, they may be formed of identical or different alloys.

The interlayer materials used in the process according to the invention are such that they have a melting point which is below the maximum temperature which is permissible for the process (see below) or such that they readily form with the parts to be bonded, a eutectiferous mixture which melts below said maximum temperature. The maximum temperature is the temperature above which irreversible changes in the microstructure of the parts occurs, which irreversible changes reduce the properties of the parts. For example, titanium alloys having a microstructure of $\alpha+\beta$ phases will be converted to a coarse grained β phase if heated to too high a temperature. Nicked alloys will be overaged if heated to too high a temperature, and niobium alloys or stainless steels may recrystallise to a coarse, equi-axed grain structure if heated to too high a temperature. All these changes will cause a deterioration in the properties of the alloys concerned.

It is believed that the interlayer materials used in the present process enable exceptionally good bonds to be obtained because they exhibit a combination of the following properties:

(i) the liquid interlayer material (or the liquid eutectiferous mixture it forms with the metal or alloy to be bonded) wets the surfaces to be bonded and also has the property of reducing or dissolving any surface oxide film on the parts to be bonded, and

(ii) local alloying of the interlayer material with the parts to be bonded at the interface does not cause a major change in the structure of the bonded parts and no insoluble intermetallic compounds are formed between any of the components of the assembly.

The amount of interlayer material used should, in principle, be as small as possible. Thin foils of interlayer material may be used, for example having a thickness of 0.0005 inch, or a thin film of interlayer material may be formed on one or both of the surfaces to be bonded by any suitable method for forming thin metallic coatings, such as electro-plating, vapour plating or metal evaporation.

In a diffusion bonding process of the type here in question, the assembly of the parts to be bonded and the interlayer should be maintained under sufficient pressure to keep the integers of the assembly in contact during the diffusion process. Pressures which lead to deformation of the metal parts are not required and should not be used. Pressures from 10 to 1000 lbf/in^2, more particularly at the lower end of this range, are preferably used.

The temperature to be used in the diffusion bonding process will depend on both the nature of the parts to be bonded and on the nature of the interlayer material. When one or both of the parts to be bonded is formed of a titanium alloy and the interlayer material is magnesium, aluminium or an aluminium/copper combination (the other part when only one is formed of a titanium alloy, being formed of any of the other materials mentioned above which can be bonded to a titanium alloy by the interlayer material in question), it is preferred to use a temperature of from 850° to 870°C. With these same interlayer materials, that is magnesium, aluminium or an aluminium / copper combination, somewhat higher temperatures may be used when neither part is formed of a titanium alloy and at least one of the parts is formed of niobium or a niobium alloy (the other part when only one is formed of niobium or a niobium alloy, being formed of a nickel alloy or, except when aluminium alone is used as the interlayer material, stainless steel), preferred temperatures in this case being from 850° to 900°C. Again with the same interlayer materials, even higher temperatures may be used when both parts are formed of a nickel alloy; in this case, preferred temperatures are from 850° to 1000°C.

When tin is used as the interlayer material, it is generally preferred to use somewhat lower temperatures; a temperature of from 650° to 870°C is, in general, preferred whatever the nature of the metal parts to be bonded.

The time required to complete bonding will depend on the temperature, longer times being required at lower temperatures and vice versa, and the amount of interlayer material used. In substantially all cases, it is not necessary to carry out the heating stage for more than 24 hours and acceptable bonds can usually be obtained in heating periods of from 1 to 3 hours.

As will be apparent to those skilled in the art, the heating stage should preferably, and in some cases must, be carried out in a protective atmosphere in order that the diffusion of the interlayer material should not be hindered by the formation of undesirable oxides or nitrides. When one or both of the parts to be bonded is formed of a titanium alloy or niobium or a niobium alloy, a protective atmosphere should be used; when the parts are formed of a nickel alloy, a protective atmosphere is not essential, but is preferred. The protective atmosphere may be provided by carrying out the heating stage in a vacuum or in an atmosphere of an inert gas, such as argon or helium.

Whilst many types of joint can be made by the diffusion bonding process according to the invention, one particularly advantageous application is in the formation of T-joints. In a structure comprising a T-joint, there is considerable stress concentration at the right angles between the "upright" and the "horizontal" of the joint, and by using the process according to the invention, it is possible to exude, at these angles, a small portion of the liquid phase formed to form a meniscus filling the angle which is retained on subsequent absorption of the bulk of the liquid phase, The formation of such a meniscus or fillet in the angles considerably reduces the stress concentration at these points and thereby considerably improves the performance of the T-joint. The other methods of diffusion bonding referred to above, that is high and low pressure solid state bonding, tend to give rise to notches or cracks at the angles between the upright and the horizontal when these methods are used to produce T-joints and it will be appreciated that due to the stress concentration at these angles, such notches or cracks lead to a disproportionately large reduction in the performance of the T-joints obtained.

In order that the invention may be more fully understood, the following examples are given by way of illustration only:—

Example 1

Two pieces of carefully cleaned Ti-6Al-4V alloy and an 0.0005 inch thick magnesium foil were assembled to form a lap joint with the magnesium foil between the two titanium alloy pieces. The assembly was pressed together under a pressure of 30 lbf/in^2 and heated at 870°C for 24 hours in a vacuum of 10^{-4} Torr.

The resulting lap joint was subjected to mechanical testing and was found to fail in the titanium alloy at a stress of 39 tonf/in^3. The shear stress in the joint itself when the tensile failure occurred was 15.5 tonf/in^2; the strength of the bond was thus in excess of this figure.

A polished and etched section was made through the interface of the joint and was examined microscopically. The line of the interface was undetectable and no change in the microstructure could be observed going from the material of one piece through the interface to the material of the other piece.

Example 2

The procedure of Example 1 was repeated three times, but using different composite copper/aluminium foils as the interlayer in place of magnesium foil and a different heating period and applied pressure. Composite foils were produced by roll bonding copper and aluminium foils in the thickness ratios of 1:2, 1:1 and 2:1, the composite foil being rolled to a final thickness of 0.0005 inch in each case. The conditions of diffusion bonding were as described in Example 1 except that the assembly was kept together under a pressure of 60 lbf/in^2 and that the heating period was only 1 hour.

Microscopic examination of the joints obtained showed that sound bonds had been obtained, but because of the different diffusion rates of aluminium and copper in titanium, bands of α-richer and β-richer material, respectively, were observed on either side of the interface. Although joints having such banded micro-structures are not so desirable as those in which there is no change in the microstructure, the former are adequate for many purposes.

More particularly, by using the combination of aluminium and copper, there is some mutual compensation for the opposite effects of aluminium and copper on the $\alpha+\beta$ Ti alloy structure; Al stabilises α Ti and Cu stabilises β Ti.

The composite foil with the 2 Al:1 Cu ratio gave the best results, that is the least banding.

Example 3

The procedure of Example 1 was repeated, but using an 0.0005 inch tin foil as the interlayer in place of magnesium foil.

Microscopic examination of the joint obtained showed that the bond was sound and that there was no microstructural banding.

When temperatures higher than 870°C were used in the diffusion bonding step, the structure of the alloy changed, becoming wholly β-phase which is generally less desirable.

Example 4

The procedure of Example 1 was repeated to form a lap joint between a piece of Ti-6Al-4V alloy and a piece of niobium.

During diffusion bonding the vacuum was 10^{-4} torr as before, but the assembly was urged together under a pressure of 400 lbf/in^2 and a temperature of 900°C was maintained for 1 hour.

The resulting lap joint has a strength of 8.5 tonf/in^2.

Example 5

Two pieces of carefully cleaned nickel alloy and an 0.0005 inch thick magnesium foil were assembled to form a lap joint; the nickel alloy was a complex heat-resisting nickel - chromium - cobalt - titanium - aluminium alloy available under the designation "Nimonic" 80A (Trade Mark). The assembly was pressed together under a pressure of 100 lbf/in^2 and heated at 900°C for 24 hours in a vacuum of 10^{-4} torr.

A joint with good bond strength and no microstructural banding was obtained.

WHAT WE CLAIM IS:—

1. A process for bonding two metal parts which are formed of the same or different materials selected from titanium alloys, niobium or niobium alloys, and nickel alloys, which comprises providing an interlayer formed of magnesium or tin between the parts to be bonded, and maintaining the assembly of the parts to be bonded, and the interlayer under sufficient pressure to keep the integers of the assembly in contact over the desired bond area and heating at a sufficiently high temperature to cause the formation of a liquid phase due to melting of the interlayer material or of a eutectic mixture formed between the interlayer material and either of the parts to be bonded, the amount of interlayer material present being such that no insoluble intermetallic compound is formed between the interlayer material and either of the parts to be bonded, the pressure and temperature being maintained until the liquid phase has diffused into the metal parts, and the assembly being maintained under a protective atmosphere during heating when one or both of the parts is formed of a titanium alloy or niobium or a niobium alloy.

2. A process according to claim 1, in which the assembly of the parts to be bonded and the interlayer is urged together during the bonding procedure under a pressure of from 10 to 1000 lbf/in^2.

3. A process according to claim 1 or 2, in which a thin coating of the interlayer material is formed on one or both of the surfaces to be bonded.

4. A modification of the process according to any of claims 1 to 3, in which, instead of an interlayer formed of magnesium or tin, an interlayer formed of a combination of aluminium and copper layers is used.

5. A modification of the process according to any of claims 1 to 3, in which, instead of an interlayer formed of magnesium or tin, an interlayer formed of aluminium is used.

6. A modification of the process according to any of claims 1 to 3, in which one of the parts is formed of a titanium alloy or niobium or a niobium alloy and the other is formed of stainless steel and the interlayer is formed of a combination of aluminium and copper layers or of magnesium.

7. A modification of the process according to any of claims 1 to 3, in which one of the parts is formed of a titanium alloy, and the other is formed of a titanium alloy, niobium or a niobium alloy, or a nickel alloy, the interlayer is formed of magnesium, aluminium or an aluminium/copper combination, and a temperature of 850° to 870°C is used during the bonding procedure.

8. A modification of the process according to any of claims 1 to 3, in which one of the parts is formed of niobium or a niobium alloy and the other is formed of niobium or a niobium alloy, or a nickel alloy, the interlayer is formed of magnesium, aluminium or an aluminium/copper combination, and a temperature of 850° to 900°C is used during the bonding procedure.

9. A modification of the process according to any of claims 1 to 3 in which both of the parts are formed of a nickel alloy, the interlayer is formed of magnesium, aluminium or an aluminium/copper combination, and a temperature of 850° to 1000°C is used during the bonding procedure.

10. A process according to any of claims 1 to 3, in which the interlayer is formed of tin and temperature of 650° to 870°C is used during the bonding procedure.

11. A process for bonding two metallic parts substantially as herein described in Example 1 or 4.

12. A process for bonding two metallic parts substantially as herein described in any of Examples 2, 3 and 5.

13. Bonded metallic parts which have

been joined by the process claimed in any of claims 1 to 3 and 11.

14. Bonded metallic parts which have been joined by the process claimed in any of claims 4 to 10 and 12.

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